BARS FROM THE INSIDE OUT: AN HST STUDY OF THEIR DUSTY CIRCUMNUCLEAR REGIONS

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Abstract The results of bar-driven mass inflow are directly observable in high-resolution *HST* observations of their circumnuclear regions. These observations reveal a wealth of structures dominated by dust lanes, often with a spiral-like morphology, and recent star formation. Recent work has shown that some of these structures are correlated with the presence or absence of a bar. I extend this work with an investigation of circumnuclear morphology as a function of bar strength for a sample of 48 galaxies with both measured bar strengths and "structure maps" computed from *HST* images. The structure maps for these galaxies, which have projected spatial resolutions of 2 – 15 pc, show that the fraction of galaxies with grand-design (GD) circumnuclear dust spirals increases significantly with bar strength, while tightly wound dust spirals are only present in the most axisymmetric galaxies. In the subset of galaxies classified SB(s), SB(rs), or SB(r), GD structure is only found at the centers of SB(s) or SB(rs) galaxies, and not SB(r). Bar strength measurements of 45 SB(s), SB(rs), and SB(r) galaxies show that SB(s) galaxies have the strongest bars, while SB(r) galaxies have the weakest bars. As SB(s) galaxies are also observed to most commonly possess dust lanes along their leading edges, this is further support of a connection between GD structure and bar-driven inflow on larger scales. There is also a modest increase in the fraction of loosely wound dust spirals at later morphological types, and a corresponding decrease in the fraction of chaotic structures. This trend may reflect an increase in the fraction of galaxies with circumnuclear, gaseous disks. The trend appears to reverse at type Scd, where the fraction of galaxies with chaotic circumnuclear dust structure increases dramatically, although these data are of poorer quality.

Keywords: Barred galaxies, galaxy classification, circumnuclear structure

1. Introduction

Bars are the most effective means of driving gas toward the centers of isolated galaxies, inflow which is often invoked to explain circumnuclear star formation and secular evolution (e.g. Kormendy & Kennicutt 2004). Observations of many barred galaxies show evidence for dust lanes along the leading edges

of the bar and these dust lanes likely trace the shocks and inflow driven by gravitational torques. The structure of circumnuclear dust within the semiminor axis of the bar can provide important information about the effectiveness of bar-driven mass transport.

It is now possible to quantitatively study the connection between bars and their circumnuclear region due to a combination of three factors: near-infrared surface photometry of a large number of nearby galaxies, a relatively straightforward measure of bar strength Q_b from near-infrared images (Buta & Block 2001) through application of the gravitational torque method of Combes & Sanders (1981), and *HST* images of many of these galaxies. In this contribution I begin with a brief overview of the classification of circumnuclear dust structure. I then apply this system to a large sample of nearby galaxies and investigate correlations between bar strength and circumnuclear structure.

2. Circumnuclear Structure in Galaxies

Martini et al. (2003a) conducted an imaging survey of 123 nearby galaxies with the NICMOS and WFPC2 cameras on *HST* to study circumnuclear dust. These data were used to develop a purely empirical classification system based on common features in the dust distribution and without regard to either the larger scale or nuclear properties of the galaxy. This system is thus complementary to the subject of this conference as it is a dust classification scheme, rather than a *dust-penetrated* classification scheme. The classification system has six categories:

Grand design (GD): Two dominant and coherent dust spirals

Tightly wound (TW): Coherent and large pitch angle dust spirals

Loosely wound (LW): Coherent and small pitch angle dust spirals

Chaotic spiral (CS): Multiple, fragmented dust lanes implying the same sense of rotation.

Chaotic (C): Dust structure without a well-defined morphology

No Structure (N): No evidence for nuclear dust structure

An example of each of these classes is shown in Figure 1.

The initial sample was culled of all galaxies with $\upsilon > 5000$ km s^{-1} and inclinations $R_{25} > 0.30$ and then each unbarred galaxy was matched with a barred galaxy of approximately the same morphological (T) type, blue luminosity, heliocentric velocity, inclination, and angular size. This resulted in an extremely well-matched set of 19 barred and 19 unbarred galaxies. The distribution of these 38 galaxies into the six circumnuclear dust classes is shown

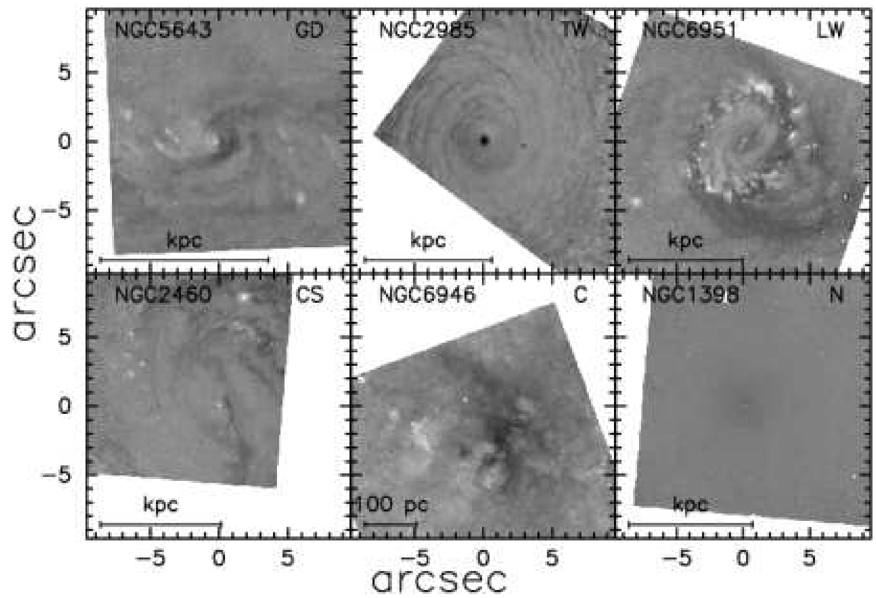

Figure 1. $(V-H)$ color maps of prototypes for the six circumnuclear morphology classes proposed by Martini et al. (2003a) and reproduced from their Figure 3.

in Figure 2. This figure clearly demonstrates two connections between bars and their circumnuclear region: GD structure is only found in barred galaxies, while TW structure avoids barred galaxies (Martini et al. 2003b). In addition, GD structure often (but not always) connects to the dust lanes along the leading edges of the bar at larger scales.

These correlations also validate the classification system itself, as they indicate that the classification bins are connected to physically relevant quantities and are not simply lost in the dust. However, these results were limited by the absence of bar strength measurements for most of the sample. Although Martini et al. (2003a) collected data on whether or not a galaxy was barred from the literature, these data varied substantially in quality and were deemed too heterogeneous to investigate correlations between the circumnuclear morphology and bar strength. In the next section, I apply this classification system to *HST* observations of a large sample of galaxies with measured bar strengths.

3. Bar Strength and Circumnuclear Structure

The new sample described here was compiled from all galaxies with published bar strengths (Buta & Block 2001; Laurikainen & Salo 2002; Block et al. 2004), visible-wavelength images with *HST*, and inclinations $R_{25} < 0.30$. Galaxies with low signal-to-noise (S/N), unfavorable placement on the WFPC2

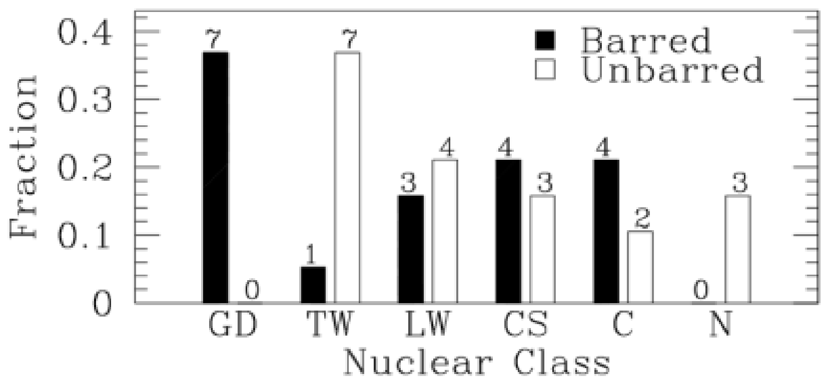

Figure 2. The frequency of the six circumnuclear classes in the sample of 19 barred and 19 unbarred galaxies studied by Martini et al. (2003b) and based on their Figure 2. GD structure is only found in barred galaxies, while TW structure appears to avoid barred galaxies.

detectors, or of type Scd ($T = 6$) or later were barred from inclusion, although Scd galaxies are discussed separately below. The final sample contains 48 galaxies of type S0 to Sc.

I used the structure map technique developed by Pogge & Martini (2002) to identify circumnuclear morphology. For this application, structure maps are superior to color maps because they can be applied to the entire (larger) field of view of the WFPC2 camera and many galaxies only have WFPC2 images. Mathematically, structure maps are:

$$S = \left[\frac{I}{I \otimes P} \right] \otimes P^t \tag{1}$$

where S is the structure map, I is the original image, P is the PSF, P^t the transpose of the PSF, and $\otimes$ is the convolution operator. Structure maps effectively emphasize structures on the scale of the PSF and deemphasize larger-scale spatial variations. In all of the structure maps shown here, dusty regions are dark and emission regions, such as star formation knots, are bright. Figure 3 shows images, color maps, and structure maps of four representative galaxies.

The galaxies were classified with the same system described in the previous section. The only modification is that instead of the fixed angular size of $19''$ employed by Martini et al. (2003a), I have chosen to classify the sample within a fixed 5% fraction of each galaxy's angular diameter D_{25}. This fractional size corresponds to a projected physical size range of $0.4 \rightarrow 2.4$kpc, while the projected physical size of the PSF is $2 \rightarrow 14$pc. Figure 4 presents structure maps of the central 5% of the 48 galaxies. There are fourteen galaxies common to this sample and Martini et al. (2003a) and as a check they were reclassified

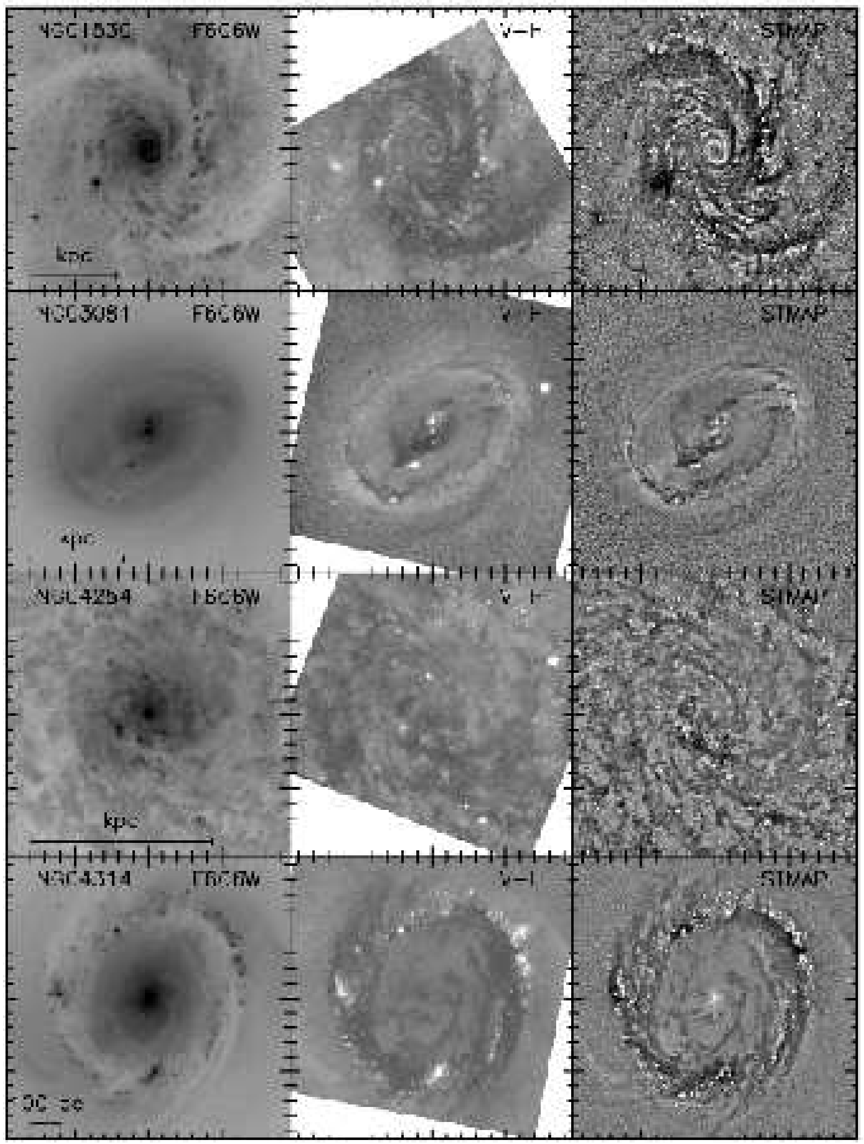

Figure 3. Comparison of V, $V - H$, and structure maps for NGC 1530, NGC 3081, NGC 4254, and NGC 4314. Both the color and structure maps effectively uncover dust features and star formation over a wider intensity range than the V image, even with the log intensity scaling shown. Dusty regions are dark, while emission line regions are light. The structure and color maps are similar, although the structure maps place greater emphasis on features near the resolution limit. Each panel is $19''$ on a side and displays north up and east to the left.

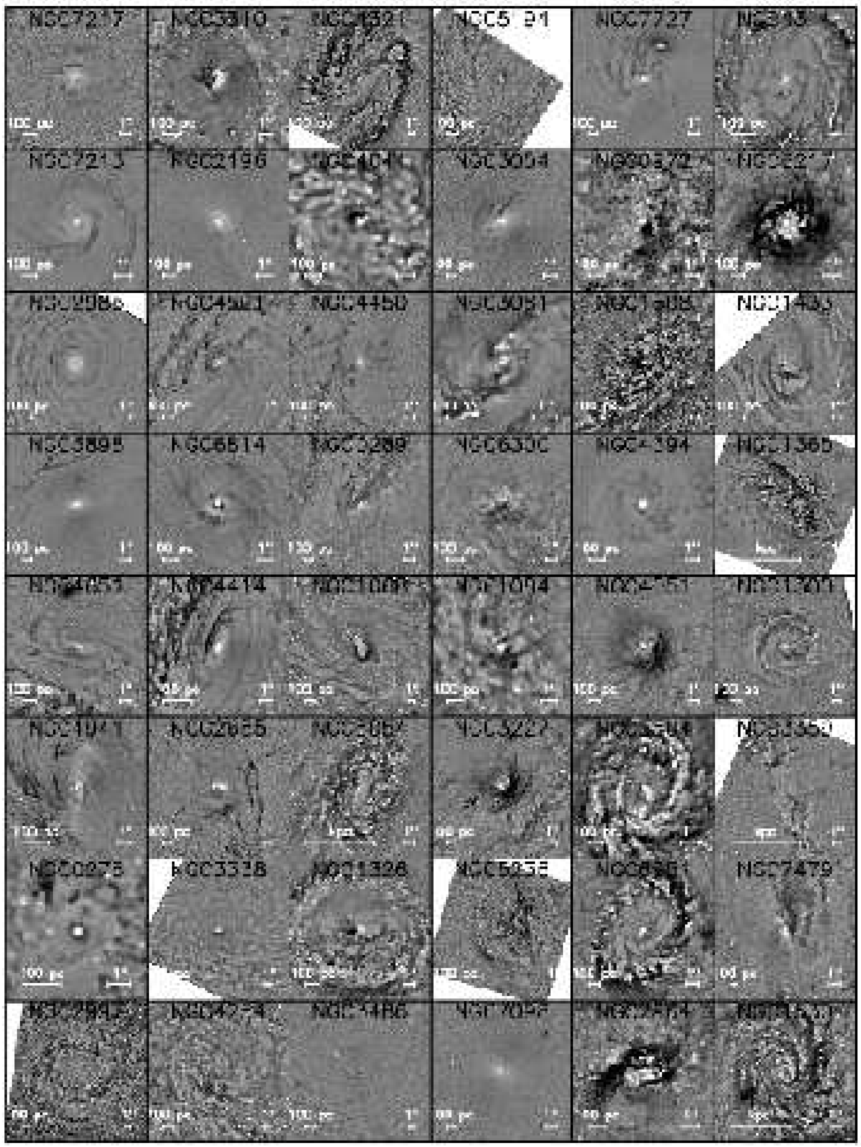

Figure 4. Structure maps for 48 galaxies with measured bar strengths ordered such that bar strength increases downward and to the right. Each panel shows the inner 5% of D_{25} from the RC3 catalog. The projected size of a kpc or 100pc is shown to the lower left, while a $1''$ scale bar is shown at lower right. North is up and east is to the left.

without reference to the prior classification. Nine received the same classification, three switched between the similar classes LW and CS, and only two (14%) changed significantly: NGC 6300 (C→GD) and NGC 4314 (LW→GD).

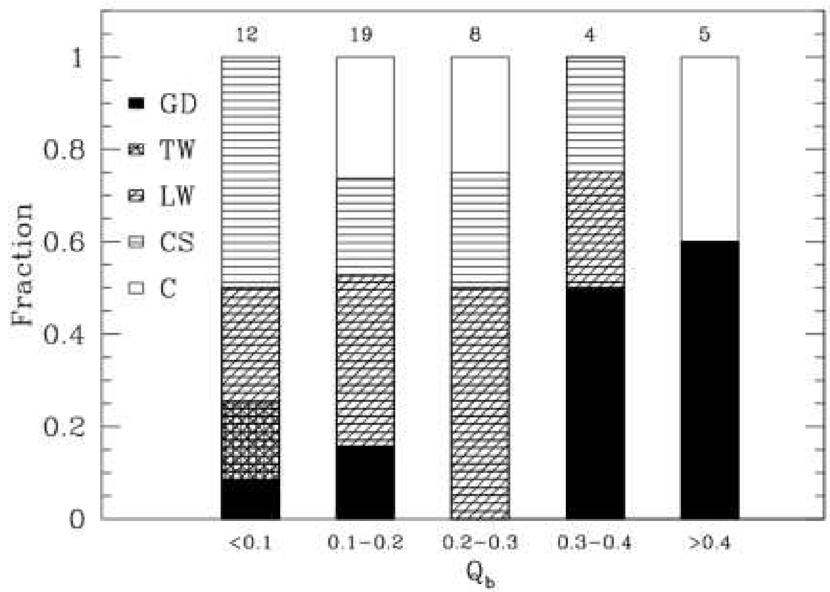

Figure 5. Fraction of each NC class in bins of Q_b. Only a small fraction of weakly barred galaxies have GD structure, while it is present in 5/9 galaxies with $Q_b > 0.3$. TW structure is only present in galaxies with $Q_b < 0.1$. The number of galaxies in each bin is shown above it.

Figure 5 shows the distribution of circumnuclear structure classes as a function of Q_b. The N class was not employed here because it was only populated by one galaxy (NGC 1398). Only four of 31 galaxies (13%) with $Q_b < 0.2$ have GD structure, while it is present in five of nine (56%) galaxies with $Q_b > 0.3$. More strongly barred galaxies are therefore more likely to have GD structure. The one GD galaxy with $Q_b < 0.1$ is NGC 6814, which was also classified GD in Martini et al. (2003a). This galaxy is listed as unbarred in the RC3, although it is classified as barred in the near-infrared.

There are also no galaxies with TW structure and $Q_b > 0.1$. Large pitch angle dust spirals are therefore not found in galaxies with a significant non-axisymmetric component. While only two galaxies were classified as TW, the probability that both would have $Q_b < 0.1$ is 4%. This result reinforces the suggestion of Martini et al. (2003b) that TW structure is only present in unbarred galaxies, and also supports recent simulation results (Maciejewski 2004).

Connection to larger-scale spirals: SB(s) and SB(r) galaxies

GD structure is preferentially found in galaxies with large Q_b and in many cases appears to be the continuation of the dust lanes along the leading edges of large scale bars, dust lanes that models show are formed by strong bars (Athanassoula 1992). Another historical measure of bar strength is whether the large-scale spiral arms originate at the ends of a bar SB(s), from an inner ring at the radius of the bar SB(r), or are intermediate SB(rs). Observations show that dust lanes along the bar are a characteristic of SB(s) galaxies, rather than SB(r) galaxies (e.g. Sandage & Bedke 1994). The presence of dust lanes suggests SB(s) bars should be strong, although hydrodynamic simulations find SB(s) spirals form with weak, fast bars and SB(r) spirals with strong, slow bars (Sanders & Tubbs 1980).

I have investigated the frequency of GD structure in all galaxies classified as SB in the RC3 (11 galaxies). This sample shows a correlation between GD structure and the connection between the bar and the large-scale spiral arms: Neither of the two SB(r) galaxies in this sample have GD structure, although it is present in $3/6$ SB(rs) galaxies and $2/3$ SB(s) galaxies. To test the connection between these classes and Q_b for a larger sample, I have computed the mean Q_b for all 45 galaxies classified as type SB(r): 0.28 (15), SB(rs): 0.35 (12), and SB(s) 0.43 (18). On average SB(s) is thus the most strongly barred type and SB(r) the weakest. However, the SB(s) sample does include more galaxies with late T type and large Q_b. If only galaxies with $T \leq 5$ are included (the range of the SB(r) sample), the mean value of Q_b for the SB(s) class decreases to 0.35 (11 galaxies). It would be valuable to revisit the SB(r)/SB(s) classification with near-infrared images.

Connection to global properties

I have also used this sample to investigate if circumnuclear structure depends on T type, luminosity, or distance. The sample was divided into early ($T \leq 1$; 10 galaxies), intermediate ($T = 2, 3$; 16), and late ($T = 4, 5$; 22) type bins. There is a gradual increase in the fraction of LW structure ($1/10 \rightarrow 4/16 \rightarrow 10/22$) and an approximately corresponding decline in the fraction of C structure ($4/10 \rightarrow 3/16 \rightarrow 3/22$). No change is observed in the fractional distribution of the remaining classes. The increase in the LW fraction at the expense of the C fraction suggests an increase in the fraction of galaxies that have circumnuclear gaseous disks, as a circumnuclear disk is required for spiral dust lanes to form (types GD, TW, LW, CS). There are no obvious trends with distance or luminosity, although this is not surprising because these galaxies span a relatively narrow range in luminosity and distance. This does indicate that the approximately factor of five range in the projected physical size of the kernel does not affect these results.

Very late-type galaxies

Figure 6 displays the nine Scd galaxies with measured Q_b in the *HST* archive, although only two meet the standards of the main sample. These two galaxies are both of type C, as are all but two of the other (lower S/N) galaxies. This may indicate that there is a dramatic increase in the fraction of galaxies with chaotic structure at very late T type, or it may only reflect the importance of high S/N for accurate classification of circumnuclear dust structure.

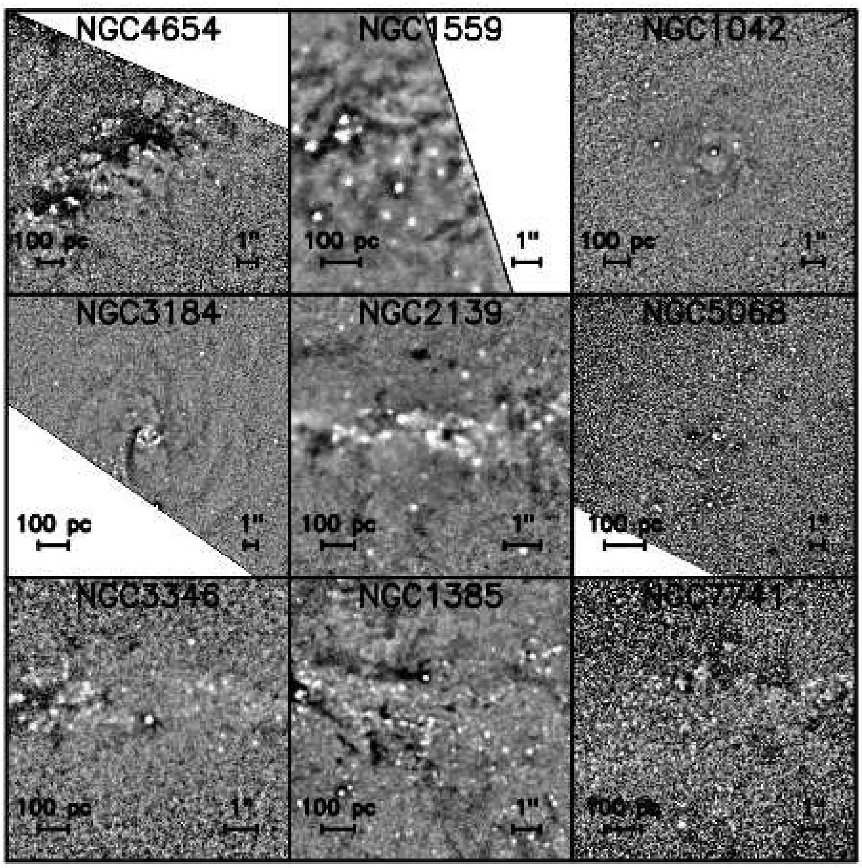

Figure 6. Same as Figure 4 for late-type galaxies ($T = 6$). Only NGC 2139 and NGC 3184 meet the same S/N and position requirements as the main sample. The structures in most panels are dominated by star forming regions, rather than dust.

4. Discussion and Summary

I have computed structure maps from *HST* data for 48 galaxies with measured bars strengths Q_b. These data clearly shown that the fraction of galaxies with GD structure increases sharply for stronger bars, while TW structure is only found in the most axisymmetric galaxies. GD structure is more common in galaxies classified as type SB(s), which are commonly observed to have dust lanes along the leading edges of their bars. Measurement of the mean Q_b for SB(s) and SB(r) galaxies shows that SB(s) galaxies generally have stronger bars. GD structure, SB(s) structure, and dust lanes along bars are therefore all correlated with bar strength. The fraction of galaxies with nuclear dust spirals increases at later T type, perhaps indicating an increase in the fraction of galaxies with circumnuclear gaseous disks. There is some evidence that this trend reverses at type Scd with an increase in the fraction of C structure, although the available data for these galaxies are significantly poorer quality.

Acknowledgments

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